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TEA LASER EMISSION ON THE SEQUENCE BANDS OF CO2.(U)
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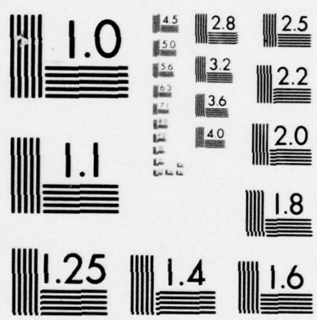

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TEA LASER EMISSION ON THE SEQUENCE BANDS OF CO_2

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(6) TEA LASER EMISSION ON THE SEQUENCE BANDS OF CO_2

by

(10) P. Lavigne, J.-L. Lachambre [redacted] G. Otis

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RESUME

Nous avons réussi à obtenir l'action laser sur les bandes séquentielles dans un amplificateur CO_2 TEA en empêchant l'oscillation des bandes régulières, soit avec une cellule de CO_2 à haute température, ou avec un interféromètre du type Michelson. Nous avons constaté que les pertes résiduelles du filtre au CO_2 à haute température réduisaient considérablement l'efficacité du laser lors de l'émission sur les bandes séquentielles. Le filtre du type Michelson, nous a permis d'obtenir une énergie de sortie de 140 mJ sur la raie séquentielle P17, dans un amplificateur TEA d'une longueur de 33 cm. Les faibles efficacités relatives obtenues indiquent que, pour produire des faisceaux intenses aux fréquences des bandes séquentielles, il serait préférable d'utiliser une combinaison oscillateur-amplificateur. (NC)

ABSTRACT

Laser emission on the sequence bands of CO_2 has been achieved in a TEA amplifier by using either a hot-CO_2 cell or a Michelson interferometer to prevent oscillation of the regular bands. It has been found that the insertion losses of the hot-CO_2 filter severely limit the energy-extraction efficiency on the sequence bands. With the Michelson filter, output energies of 140 mJ on the P17 sequence line have been produced in a 33-cm long TEA amplifier. The relatively low efficiencies obtained suggest that the generation of high-intensity laser beams at the sequence-band frequencies would require the use of an oscillator-amplifier combination. (U)

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1.0 INTRODUCTION

Recently, small-signal gain coefficients as high as 1.5% cm^{-1} have been measured [1] in a TEA-CO_2 amplifier on the $00^{0}2$ - $(10^{0}1$ - $02^{0}1)_{I,II}$ sequence bands of CO_2 in the 9-10 μm region. As the lower vibrational levels of these transitions lie about 3600 cm^{-1} above ground state, they absorb radiation very weakly at normal temperatures. According to published theoretical results [2], atmospheric CO_2 constitutes 50% of the total molecular absorption at sea level in a clear atmosphere under conditions corresponding to the mid-latitude winter. It is therefore expected that TEA-CO_2 high-intensity laser radiation on the sequence lines would propagate through the atmosphere with less attenuation and give greater returned signals from illuminated targets than the regular emission lines.

In this document, we report TEA-laser emission on the sequence lines and we evaluate two different filtering techniques successfully used to prevent laser action on the regular lines and to maximize the output on the sequence bands. This work was performed at DREV between February and September, 1977 under PCN 33H01, Laser Applications in Surveillance and Remote Sensing Technology.

2.0 THEORY

The strong coupling that has been observed [1,3] between the $00^{0}1$ and $00^{0}2$ levels of CO_2 indicates that the antisymmetric stretching levels form an energy reservoir that feeds a particular ν_3 overtone of rank n depopulated by stimulated emission. In principle, the same amount of optical energy should be available in a pulsed laser on each of the $00^{0}n$ - $[10^{0}(n-1), 02^{0}(n-1)]_{I,II}$ transitions around 10 μm, if all the lower levels are rapidly deactivated through collisional exchanges.

In this approximation, the laser energy density E_n extracted from a TEA laser oscillating on a single transition is given by the expression [4]:

$$E = (\gamma_n^c/\gamma_n)h\nu \left[\sum_{k=1}^{\infty} N_k^i - \sum_{k=1}^{\infty} N_k^{th} \right] \tag{1}$$

where $h\nu$ represents the transition energy; γ_n^c and γ_n, the total and coupling loss coefficient at the lasing frequency; $\sum_k N_k^i$, the total number of molecules excited in the ν_3 overtones; and $\sum_k N_k^{th}$, the number of molecules in the reservoir when the small-signal gain of the transition of interest is equal to the losses of the optical cavity. In the harmonic oscillator approximation,

$$\sum_{k=1}^{\infty} N_k^i = \frac{N_1^i}{1-e^{-h\nu_3/kT_3}} = \frac{\alpha_1/\sigma_1}{1-e^{-h\nu_3/kT_3}}$$

and,

$$\sum_{k=1}^{\infty} N_k^{th} = \frac{N_n^{th}\; e^{(n-1)h\nu_3/kT_3}}{1-e^{-h\nu_3/kT_3}} = \frac{\gamma_n/\sigma_n\; e^{(n-1)h\nu_3/kT_3}}{1-e^{-h\nu_3/kT_3}} \tag{2}$$

where k is the Boltzmann factor and $h\nu_3$, the energy of the antisymmetric stretching mode ν_3. T_3 represents the vibrational temperature of the ν_3 mode and α_1, the small-signal gain coefficient of the regular band

transition (n=1). In particular, in a given TEA-CO_2 laser, the ratio E_2/E_1 of the energy densities that can be extracted on the sequence (n=2) and on regular (n=1) bands is given by the equation:

$$\frac{E_2}{E_1} = \frac{(\gamma^c_2/\gamma_2)_{opt}}{(\gamma^c_1/\gamma_1)_{opt}} \left[\frac{1 - (\gamma_2\sigma_1/\alpha_1\sigma_2)\ e^{h\nu_3/kT_3}}{1 - \gamma_1/\alpha_1}\right] \qquad (3)$$

where σ_1/σ_2 represents the ratio of the radiative cross sections that amounts to 0.5 for a harmonic oscillator [5]. The $(\gamma^c_n/\gamma_n)_{opt}$ factors refer to the losses of the laser when the coupling mirror is used to optimize the output energy of the n=1 and n=2 transitions respectively.

It is seen from Eq. 3 that the relative extraction efficiency E_2/E_1 increases with the vibrational temperature T_3 as well as with the excess gain α_1/γ_2 and the coupling ratio $(\gamma^c_2/\gamma_2)_{opt}$. At practical T_3 temperature ($T_3 < 5000$ K), $\alpha_1 > \alpha_2$ so that $(\gamma^c_2/\gamma_2)_{opt} < (\gamma^c_1/\gamma_1)_{opt}$, and the only way to improve the relative extraction E_2/E_1 is to make T_3 and, consequently, α_1 as high as possible. Furthermore, as the higher gain regular transitions must be filtered out to force the energy extraction through the sequence transitions, the length of the amplifying medium and, consequently, the total output energy are limited by the attenuation and selectivity of the filter. In practice, the insertion losses of the filter will degrade the coupling factor γ^c_2/γ_2 and further decrease the relative efficiency of a sequence band TEA-CO_2 laser.

3.0 EXPERIMENTAL

3.1 Filtering with hot CO_2 cell

Laser action on the sequence bands is limited to lines which are far enough from the regular transitions to allow selective filtering. In a TEA-CO_2 amplifier [1], at a vibrational temperature T_3 of 1800 K, the ratio of the gain coefficients α_2/α_1 is about 1/3. Therefore, pure laser emission on the sequence bands is limited to lines separated by at least one homogeneous line width (≃4 GHz) from the CO_2 regular transition frequencies.

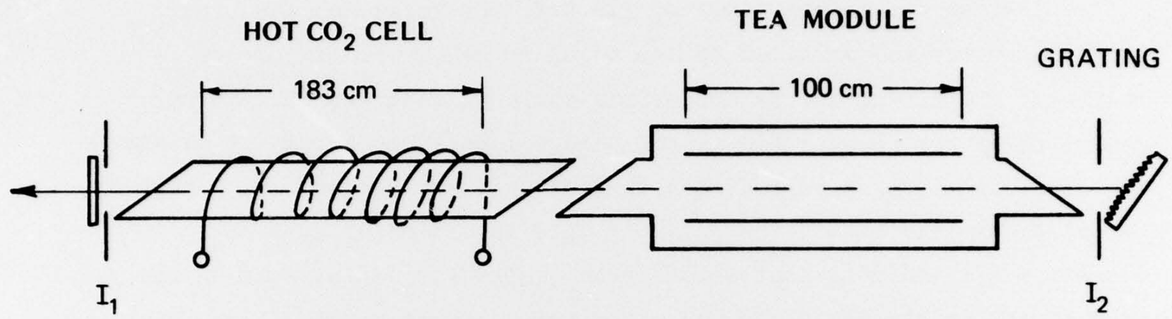
In a first experiment, TEA-laser emission on the sequence bands was achieved using a hot CO_2 cell frequency filter [5], as schematically illustrated in the upper part of Fig. 1. The 100-cm discharge TEA module was placed in a 410-cm optical cavity formed by a concave grating (15-m radius of curvature, 75 gr/mm and a ZnSe coupling mirror (80% reflectivity). The grating was tuned for emission on the P17 line of the sequence 10.4 μm band that lies about 11.2 and 42.2 GHz from the P20 and P18 regular lines respectively [6]. A 183-cm glass cell was inserted between the TEA module and the coupling mirror. Then, this cell was filled with 610 torr of CO_2 and heated to 635 K so that it could absorb over the whole emission-line of the TEA unit. To prevent laser emission on the regular P20 line, the heated part of the cell L_H must be chosen so that:

$$L_H > \alpha(P20)L_d/0.024$$

where L_d is the discharge length of the amplifying medium and 0.024 cm^{-1} the measured absorption coefficient of the P20 line by CO_2 heated to 635 K.

At an excitation level of 125 J/ℓ, the total energy output on the sequence P17 amounted to 185 mJ in an He-CO_2-N_2 mixture of 70-20-10. No direct energy comparison could be made with the energy generated on the regular P20 in the same volume since permanent damage to the coupling mirror resulted when the hot cell was pumped down. However, calculations from saturation data obtained in a similar type of discharge [7] indicate that about seven joules (19 J/ℓ of optical energy were stored in the active volume. The very low efficiency (1/40) of the energy extraction on the sequence bands follows from the poor coupling-to-loss ratio ($\gamma_2^c/\gamma_2 \simeq 0.1$), as determined from Fig. 1. A large amount of cavity losses was due to the insertion losses of the hot-CO_2 filter. This is illustrated in Fig. 2 where the absorption coefficient of CO_2 at 630 K is given as a function of pressure for the P20 and P17 lines. The absorption coefficient of the P20 increases linearly with the pressure in the Doppler region and gradually levels up at a value of about 0.024-cm^{-1} as the line becomes collisionally broadened. The absorption coefficient of the P17 behaves the same way at pressures lower than about 150 torr. At higher pressures, the wings of the P20 line of the 00^01 - $(10^00, 02^00)_I$ band, and of the R23 and R24 lines of the 01^11 - $(03^10 - 11^10)_I$ band, contribute to the absorption of the P17 line so that the absorption coefficient increases again with the pressure. These insertion losses are a limiting factor to the energy extraction efficiency on all the lines.

If one uses $\gamma_2^c/\gamma_2 = 0.1$ and assumes that the limiting apertures of the irises were completely filled by the radiation, Fig. 1 indicates that five J/ℓ of optical energy should be available on the P17 line at an excitation level of 125 J/ℓ, which corresponds to 25% of the calculated energy available on the P20 line. This ratio must be compared with the 40% ratio predicted from Eq. 3 with $\gamma_1 = \gamma_2 = 0.009$ and with the measured values of 0.04 cm^{-1} and 1850 K for α_1 and T_3 [1]. This discrepancy could easily be related to the difficulty of precisely evaluating the mode volume.



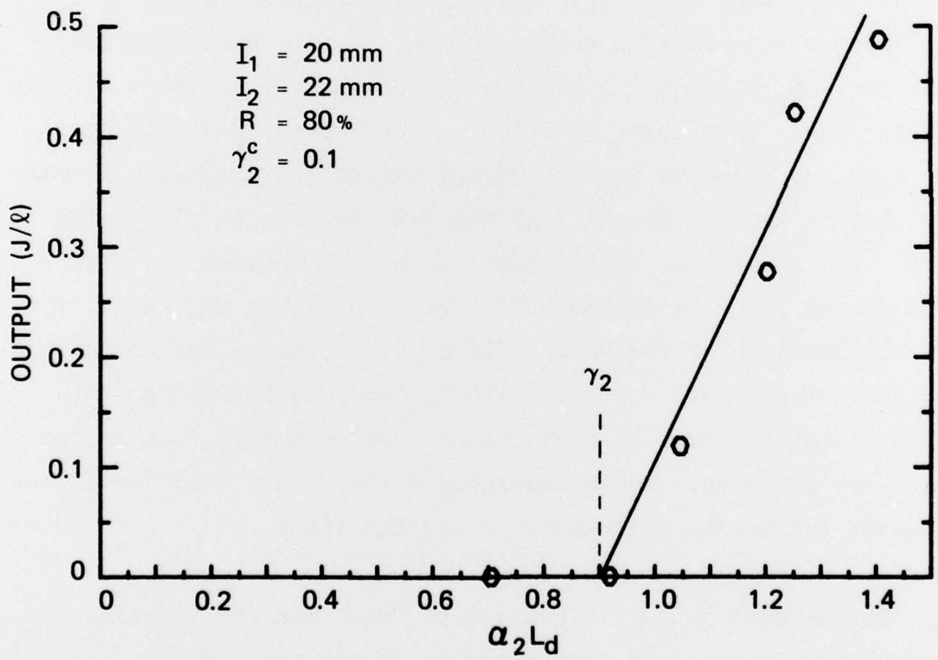


FIGURE 1 - Variation of the output energy density on the sequence P17 versus the single-pass gain coefficient ($\alpha_2 L_d$) using the hot-CO_2 cell filter. These data were obtained by varying the excitation electrical energy density between 0 and 125 J/ℓ.

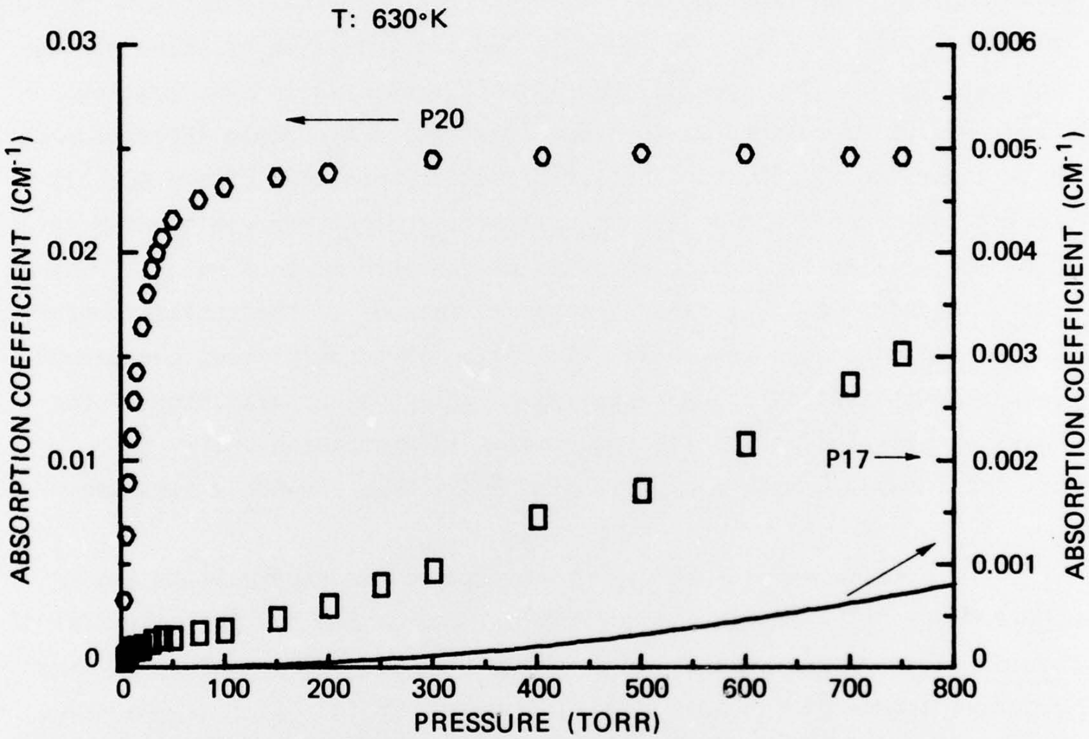


FIGURE 2 - Measured variation of the absorption coefficient of hot CO_2 (630 K) at the regular P20 and sequence P17 frequencies versus pressure. The continuous curve represents the contribution of the wings of the P20 line to the absorption at the line center of the P17 line calculated by assuming a Lorentzian lineshape.

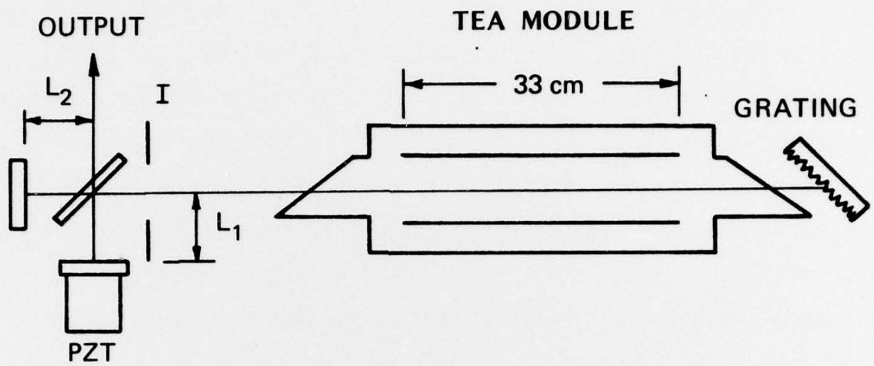
3.2 Filtering with a Michelson interferometer

A frequency filter, with much less insertion loss than the hot-CO_2 one, can be realized by using a Michelson interferometer as the coupler. The experimental arrangement schematically represented in the upper part of Fig. 3 was used to realize TEA-laser emission on the sequence lines. The optical cavity was formed by a concave grating (10-m radius of curvature, 75 grooves/mm) and a Michelson interferometer both separated by 245 cm. The interferometer was made of two totally reflecting mirrors and a Ge-beam splitter. One mirror was mounted on a piezo-translator for tuning purposes and the other, on a coarse translation stage to allow relative length variations of the interferometer arms. The discharge length was limited to 33 cm to prevent permanent damage to the optical components and to allow easier quenching of the laser oscillation on the regular bands. An excitation energy of 200 J/ℓ insured a high α_2/α_1 ratio in a 73-18-9: He-CO_2-N_2 mixture.

The lower part of Fig. 3 represents the threshold levels of the P20 and P17 lines in the amplifying section and the reflectivity of the interferometer calculated assuming an ideal beam splitter. The relative length of the arms must be set so that the P17 line was above threshold when the interferometer was tuned to prevent laser oscillation on the P20 line. This was achieved when $|L_1-L_2| \simeq c/4\Delta f$, where Δf represents the frequency difference between the sequence line and the nearest regular line. Figure 4 illustrates the variation of the total output energy as a function of the tuning range of the interferometer. The grating is oriented to maximize the laser output on the P17 sequence line and a 11-mm iris is placed near the beam splitter. The output as filtered by a monochromator (Spex model 1800 II) successively aligned for transmission of the P20, P17 and P18 lines is likewise shown. As

seen on the first set of data, when the P20 line was brought below threshold, laser emission occurred on the P17 and the P18 lines. These curves were obtained when the difference of the interferometer arm lengths amounted to about 6.5 mm so that the reflectivity of the P17 line was near its maximum while the reflectivity of the P20 line approached its minimum. Coarse displacement of one mirror by 0.5 mm gave conditions for which the P20 and P18 regular lines were brought together below threshold, as illustrated by the second set of data.

The Michelson coupler behaves like a variable-reflectivity mirror. With a 16-mm iris, the maximum energy on the P17 line occurred at a reflectivity of about 85% and amounted to 140 mJ. This corresponds to an energy density of 1.7 J/ℓ. When the grating was properly oriented, the maximum energy on the P20 line reached 560 mJ, which gives a density of 7 J/ℓ. The measured ratio E_2/E_1 of 25% is to be compared with the 70% ratio calculated from Eq. 3 if one assumes a coupling factor γ_2^c/γ_2 of 1 and a T_3 temperature of 1850 K. This descrepancy could be explained by the difference obtained in the number of transverse modes oscillating at the P17 and the P20 line frequencies as a consequence of the large difference in net gains. As seen in Fig. 5, the pulse shape also reflects this difference in excess gain. The lower gain of the P17 line results in a less efficient gain switching which leads to much wider pulses.



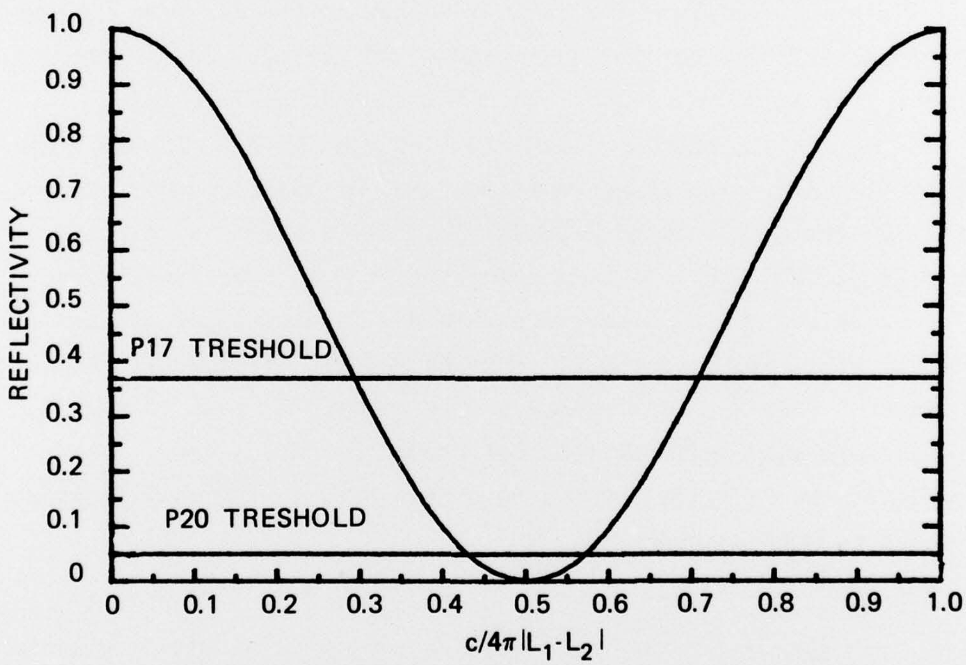


FIGURE 3 - Schematic diagram of the arrangement comprising a Michelson interferometer to prevent oscillation of the regular lines and calculated reflectivity of the interferometer versus tuning.

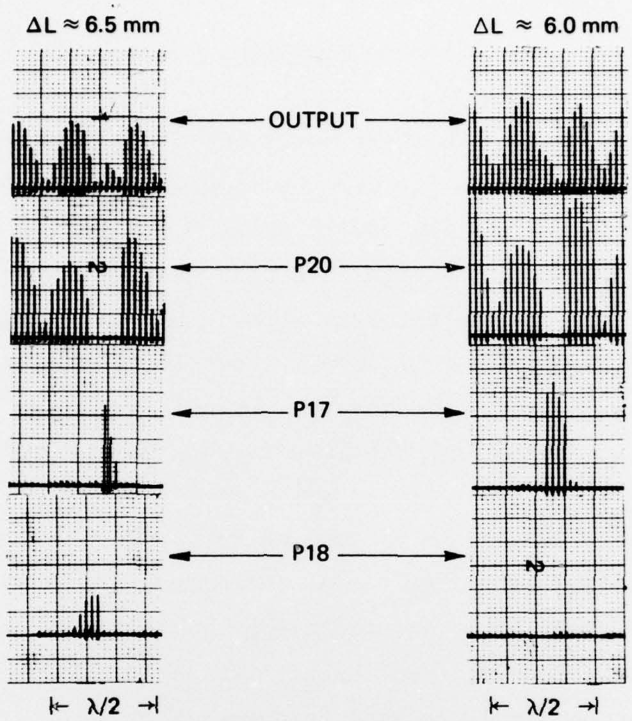


FIGURE 4 - Variation of the total laser output and of its relative P20, P17 and P18 lines content versus the tuning of the interferometer.

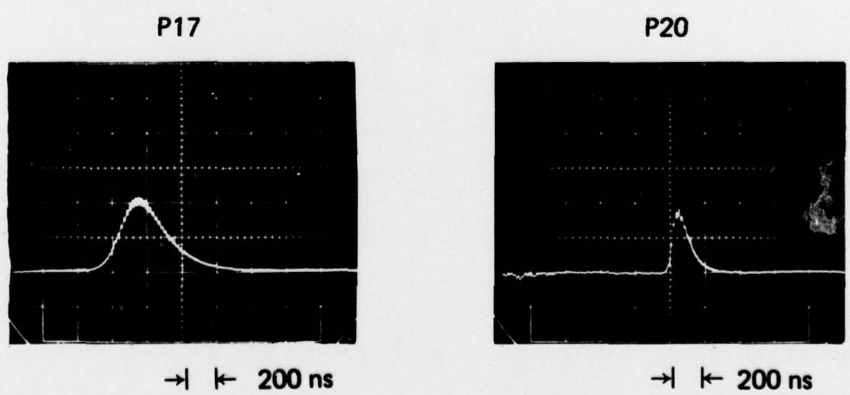


FIGURE 5 - Pulse shape of the P17 and P20 lines outputs.

4.0 CONCLUSION

TEA laser action has been achieved on the sequence transitions of CO_2 by filtering out the regular lines either with a hot-CO_2 cell inserted in the cavity or with a Michelson interferometer as the coupling mirror. The high insertion losses of the hot-CO_2 filter at high pressures render that method inefficient in TEA-amplifier systems. The Michelson coupler allows a better extraction of the optical energy, but possible damage to optical components limits its practical use to systems with single-pass gain coefficients ($\alpha_1 L_d$) smaller than about 2. In fact, it was possible to obtain, on the sequence P17, only 25% of the maximum energy produced on the regular P20 line in a module with $\alpha_1 L_d \simeq 1.5$. Therefore, the low efficiency of the sequence band TEA-CO_2 oscillator suggests the use of a high-gain short-length oscillator followed by amplifiers to efficiently generate high energies at the sequence band frequencies.

5.0 ACKNOWLEDGEMENTS

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